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Modeling the contribution of ephemeral gully erosion under different soil managements: A case study in an olive orchard microcatchment using the AnnAGNPS model

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ABSTRACT

A study was undertaken into the environmental and economic impacts of different soil management strategies, spontaneous grass cover with and without gully control (SC/SCGC) or conventional tillage with and without gully control (T/TGC), based on the experimental results obtained in an 6.1 ha olive crop microcatchment. Initially, 2 years of rainfall–runoff–sediment load data series, (34 events) recorded under the current management (SCGC), was used for the calibration of the AnnAGNPS model at event and monthly scales providing suitable adjustments of runoff, peak flow and sediment loads ($E>70$, $r>0.85$).

Ephemeral gullies were also identified using aerial orthophotography and field work. The module of the AnnAGNPS model for simulating ephemeral gully generation and the tillage operations based on a bibliographical review were used to compare different scenarios and to perform a 10 year-analysis. The results showed mean runoff coefficients of 10.0% for SC/SCGC and of 3.2% for T/TGC while the average sediment loads were 2.0 t$*$ha$^{-1}*$year^{-1} (SCGC), 3.5 t$*$ha$^{-1}*$year^{-1} (SC), 3.3 t$*$ha$^{-1}*$year^{-1} (TGC) and 4 t$*$ha$^{-1}*$year^{-1} (T). Significant differences in sediment sources (rill/inter-rill erosion and ephemeral gullies) were evaluated between SC (46% of gully contribution) and T (19% of gully contribution), in order to optimize the environmental and economic effort required in each case. Finally, the annual costs associated with soil losses were estimated (<1 €$*$ha$^{-1}*$year^{-1}). SC was the most profitable alternative for soil management. Despite the additional reduction in soil losses of the SCGC approach, the higher cost of its implementation and the minor effect on yield losses in the medium term suggest that without additional support (such as subsidies for gully control measures), farmers would have not an obvious incentive to use it.

1. Introduction

At a global scale, soil erosion is a major environmental problem, resulting, among other outcomes, in a threat to the sustainability of agricultural production and the quality of surface waters in many regions of the world (Wilkinson and McElroy, 2007). Water and aeolian erosion affects 16% of European territory, with the Mediterranean countries of Spain and Portugal facing the most serious risk of erosion, (PESERA, 2004). Due to the severe sloping nature of the landscape, high erosion rates can be expected in agricultural regions in Spain planted with vines, almond and olive trees, which are very important to the Spanish economy. These crops are common in precisely the areas of Spain most prone to desertification (De Santiesteban et al., 2006).

Erosion due to ephemeral gullies and gullies in cultivated areas in the Mediterranean area is known to contribute significantly to the total soil losses and is one of the major processes of land degradation (Martinez-Casasnovas et al., 2005; Oostwould-Wijdenes et al., 2000; Poesen et al., 2003). This contribution may vary considerably according to the spatial scale, temporal scale and environmental controls, such as soil type, land use, climate and topography (Poesen et al., 2003). For instance, De Santiesteban et al. (2006), working in Navarre in a small catchment with winter cereals over a period of 6 years, found that ephemeral gullies accounted for 66% of the erosion and for 17% in another small catchment with vineyards over a period of 2 years. In the case of olive crops, most studies have dealt with quantifying sheet and rill erosion in plots (e.g. Fleskens and Stroosnijder, 2007; Francia et al., 2006; Gómez et al., 2008a, 2009). Measurements at larger scales than the plot scale, where the hydrological and erosive processes are more complex and more difficult to evaluate, are rare and data is scarce in the Mediterranean environment (De Vente and Poesen, 2005). Although plot studies and field surveys are essential, it is difficult to

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extract from them a full picture of the real erosive situation at other scales, especially when the erosive effects of concentrated flow are not measured.

Empirical or physically based erosion models have been used extensively to complement erosion measurements at different scales in order to understand the complex interactions of the different erosion processes at basin scales and to assess adequate alternative management practices. A wide range of models exist and are used for simulating sediment transport and the determination of soil loss. These models differ in terms of complexity, processes considered and the data required for model calibration and model use (Merrit et al., 2003). A common feature of most of these models is their focus on a limited number of soil erosion and sediment transport processes. Most models consider rill and inter-rill erosion whereas only a few models specifically consider gully and bank erosion (De Vente and Poesen, 2005).

Among the models including gully erosion are those of Capra et al. (2005) who suggested empirical relationships between gully attributes and rates of soil loss derived from gullies. Also Souchére et al. (2003) developed the STREM ephemeral gully model to estimate the erosion level of the main runoff collector networks within agricultural catchments. This model used an expert-based approach that combined field experiment results and knowledge about erosion processes with agricultural practices. Hessel and Van Asch (2003) studied the process of erosion in a small semi-arid catchment of 3.5 km^2 in the Loess Plateau in China using a simple slope stability sub-model to predict gully erosion used as an input to the Limburg Soil Erosion Model (LISEM; De Roo et al., 1996). Using this approach, they estimated soil losses derived from gullies at 77 tonnes in a six-month period in the study area. The Ephemeral Gully Erosion Model (EGEM, Woodward, 1999) has been extensively used to assess ephemeral gully erosion from agricultural fields. Nachtergaele et al. (2001) evaluated the EGEM model in agricultural areas of Spain and Portugal, concluding that although the model predicted the gully volumes well, gully cross-sections were not well described due to the difficulties in simulating the effect of stones on the soil profile and the contribution of both Hortonian and saturation overland flow to the ephemeral gully erosion process.

Gordon et al. (2007) has extended the capabilities of EGEM through revisions incorporated into the AnnAGNPS model (Bingner et al., 2009), enabling it to account for ephemeral gullies in watershed studies. These capabilities include: (1) allowing for unsteady, spatially-varied runoff or storm events; (2) extending the gully by the upstream migration of a headcut, thereby removing the ephemeral gully length as an input parameter; and (3) determining channel width from discharge.

Finally, one area of 2.5 Mha is dedicated to olive orchard land-use in Spain (CAP — Consejería de Agricultura y Pesca, 2008) while about 75% is concentrated in the Southern region of Andalusia. The extensive areas of olive plantations in Andalusia, which were historically cultivated in marginal hilly soils where many other crops were not unsustainable, have a large economic, cultural and environmental importance, especially in the rural areas. Since the Mediterranean areas are characterized by the limited rainfall, the traditional orchard management has been based on reduced tree densities, the control of canopy size by pruning and the intensive weed control to avoid competition by water stored in the soil profile. The different soil management systems applied in olive orchards have notable effects on runoff and soil losses (Francia et al., 2006; Gómez et al., 2003, 2009) as well as on the costs and the economic balance of farmers. In addition, the productivity of the crop has a very high variability – from less than 500 kg(olive)$*$ha^{-1} until more than 15000 kg(olive)$*$ha^{-1} (CAP — Consejería de Agricultura y Pesca, 2002) – and many farmers of marginal olive groves with a low production, try to minimize the cost of the management operations since without EU subsidies, they would not have economic benefits. The ecological sustainability requires that most economic resources and efforts were invested in the main causes of soil and water degradation.

This manuscript presents the results of a two-year study, using a combination of field measurements in an experimental microcatchment covered by olive trees in southern Spain and the AnnAGNPS model with the improved ephemeral gully module. We chose this model because: 1) the model allows us to evaluate the soil losses derived from both rill and inter-rill erosion processes; 2) the model was designed to simulate runoff and erosion in predominantly agricultural catchments; 3) the model has relatively few requirements for calibration (León et al., 2004) and it is a useful tool for the study of different scenarios and management alternatives; and 4) previous studies support its application under Mediterranean conditions (Licciardello et al., 2007; Taguas et al., 2009). Our main objective is to evaluate the influence on total soil losses, and its distribution in gully and interrill erosion, for the different management strategies available to farmers in marginal olive orchards in mountainous areas in the region, and explore the economic implications of the different management strategies.

2. Material and methods

2.1. Study site

The Puente Genil microcatchment is situated in the southwestern portion of the province of Cordoba, Spain (37.4°N, −4.8°W, Fig. 1). The drainage area is 6.1 ha, with a mean elevation of 239 m and a mean slope of 15%. The climate is typical of the Mediterranean region, with a mean annual rainfall of around 400 mm. The average temperature of the hottest month (July) is 26.5 °C and of the coldest month (January) is 8.4 °C. The soil is shallow and has been classified as Cambisol (F.A.O., 2006) with a loamy sand soil textural class, a surface organic matter content close to 1.6% and mean values of bulk density in the top soil of 1.61 g/cm^3 (Taguas et al., 2010a). The olive trees were about 13 years old at the start of the experiment in April 2005, planted with a 7 m × 7 m tree spacing (Fig. 2a, b, d). The management system includes spontaneous grass cover that grows in winter and spring in the no-tillage areas. There are one or two weed controls per year (October and March/April or March/April) using herbicides around every tree and the tractor is driven over twice to kill the strips in the inter-tree lanes mechanically in April. Harvesting is a manual process and takes place at the end of autumn.

Previous studies, such as Taguas et al. (2010b), identified a total of 17 ephemeral gullies (Fig. 2a–b) in the microcatchment with a total length of 635.8 m and a length density of 10.4 km/km^2.

In the summer of 2005, in order to reduce gully erosion, rock barriers were placed inside the gullies as a protection measure (Fig. 2a–b).

In April 2005 a gauging station was set up at the outlet of the microcatchment (Fig. 2c). Rainfall was measured with a rain gauge (Hobo Event 7852 M) that recorded rain intensity at 1 min intervals (resolution = 0.2 mm$*$pulse^{-1}). The discharge was measured with a long-throated trapezoidal flume, while the bed load was not measured due to its low significance. The flume was designed according to the specifications defined by Clemmens et al. (2001). The water level was measured in a nearby stretch of water, upstream of the critical flow section, by an ultrasonic sensor (Milltronics Ultrasonics), in conjunction with an automatic sampler (ISCO 3700C) that retrieved samples of 200 ml of water and sediment at 15 min intervals. A data logger, Datataker DT 50, was used to organize the instruments' activity and to record the data. The samples were oven-dried to determine the instantaneous sediment concentration, and this is used, in conjunction with the associated instantaneous discharge throughout the runoff hydrograph, to produce the total soil loss from a runoff event (more details in Taguas et al., 2010a).

2.2. Description of the AnnAGNPS model

AnnAGNPS (Bingner et al., 2009) is a continuous, distributed parameter model, simulating surface-runoff volume, peak flow rate, sediment and pollutant transport from an agricultural watershed. The model is

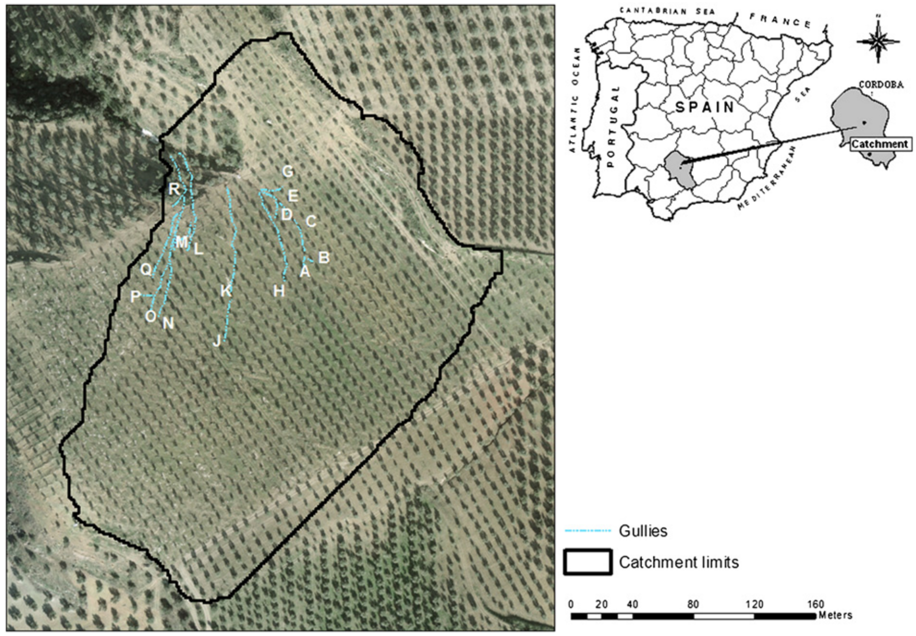

Fig. 1. Catchment location (right) and ephemeral gullies identified in the study microcatchment (left).

the continuous version of the single event AGricultural NonPoint Source model, AGNPS (Young et al., 1989). The basic modeling components are hydrology, sediment, nutrient, and pesticide transport, although the present study was concerned only with the hydrology and sediment modules (Fig. 3a). The minimum spatial units where the main physical processes are modeled are represented by the cells of a watershed that are defined as land area with homogeneous bio-geophysical properties, used to provide spatial variability in the landscape and determined from climate, land use, soil properties and topographical information. The topographical parameters “critical source areas” and “minimum source channel lengths” are required by TOPAGNPS algorithms to represent landscape in cells and streams. The constituents are routed from their origin within the cells and are either deposited within the cells, the stream channel system, or transported out of the watershed (Fig. 3b; Bingner et al., 2009).

The hydrology component of AnnAGNPS applies the SCS Curve Number technique (SCS — Soil Conservation Service, 1985) to generate daily runoff in the cells from precipitation. The total daily runoff is determined for each channel and for the outlet, using the TR-55 (SCS — Soil Conservation Service, 1986) by adding the travel times. The time

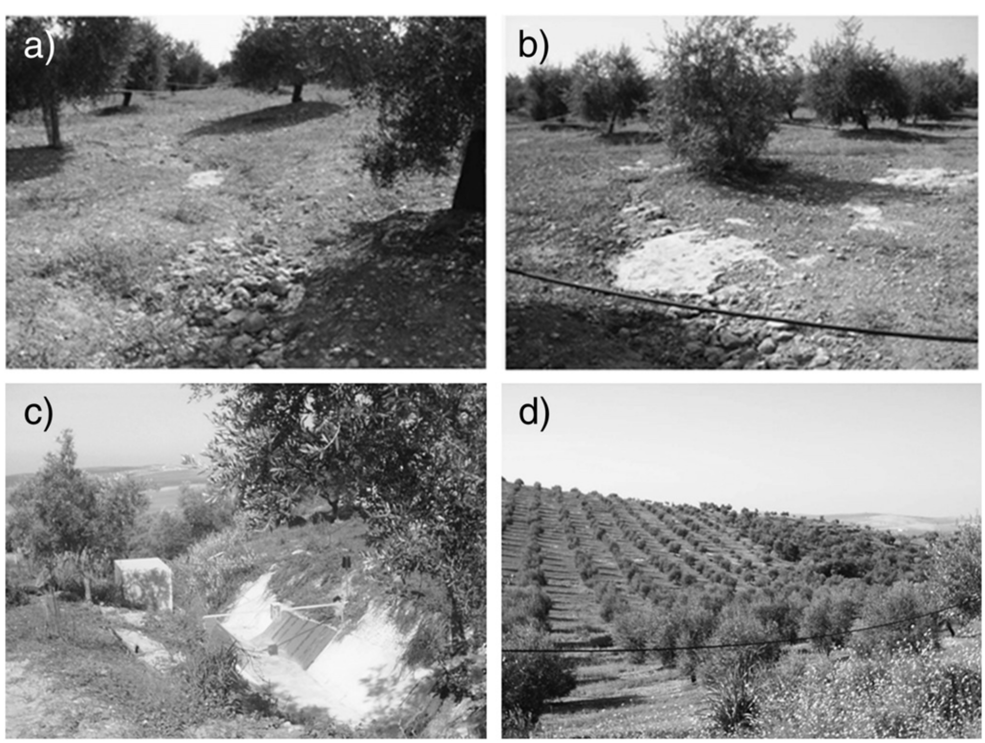

Fig. 2. a)–b) Gullies with rock barriers and organic residues (September 2007); c) gauging station in the study microcatchment (left); d) view of a hillslope with natural vegetation cover (right, January 2008).

of concentration (calculated from AGFLOW and TOPAGNPS), the calculated runoff volume and the storm type of TR-55 are required for the calculation of the value of the peak discharge and the corresponding time (Bingner et al., 2009).

Sheet and rill erosion is calculated for each event using RUSLE 1.05 technology (Renard et al., 1997) with the possibility of having different values of the RUSLE parameters in each cell. The Hydro-geomorphic Universal Soil Loss Equation (HUSLE) is used for quantifying the delivery ratio of sediment from cells to channel (Bingner et al., 2009). Finally, once in the channel, for each particle-size in a rectangular channel, the sediment load is determined by the integral for the base time of the hydrograph for sediment transport capacity when this is greater than the incoming sediment load (for algorithms of sediment transport see Bingner et al., 2009). The sediment transport capacity and the unit-width water discharge are based on the parameters at the upstream end of the channel. Bank and bed erosion was not considered in the catchment because of the abundant vegetation and residues protecting the reach and due to its short length (Fig. 2c).

To simulate ephemeral gully erosion, AnnAGNPS requires the peak discharge to be determined, together with the total runoff volume and the hydrograph corresponding to the incision point where a gully starts its development (hereafter nickpoint), the rainfall event, the Curve Number and the storm type (Bingner et al., 2009; Gordon et al., 2007). The user must define the drainage area (or contributing area), the local slope on the nickpoint (initial point of the gully incision) and the erosion layer depth of the nickpoint, but defaults are used to describe these based on field properties. AnnAGNPS predicts the development of the gully by modeling the gully incision in the nickpoint,

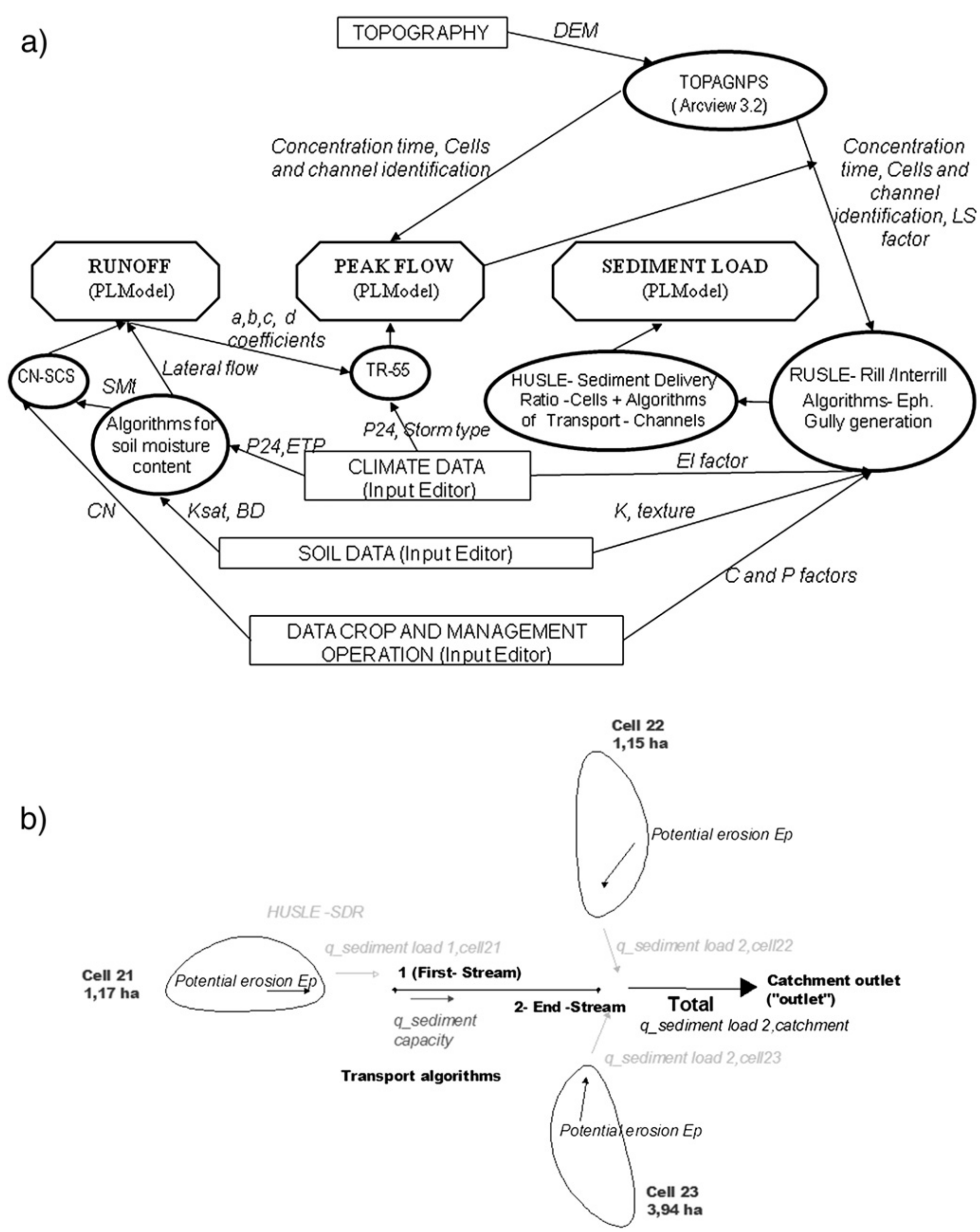

Fig. 3. Description of AnnAGNPS model: a) summary of the algorithms and techniques used, variables and data required by the AnnAGNPS model (DEM is the Digital Elevation Model; TopAGNPS, Input Editor and PL-Model are the executable programs; *EI*, *K*, *LS*, *C* and *P* factors are the component of RUSLE model, rainfall erosivity, soil erodibility, slope length, crop-management factor and support practice factor; *SMt* is the current soil moisture; *CN* is Curve Number, *ETP* is evapotranspiration, *P24* is the daily rainfall depth; *Ksat* is the saturated hydraulic conductivity; *BD* is the bulk density; *a*,*b*,*c*,*d* are the coefficients depending on the rainfall distribution type, TR-55 methodology). b) Description of the spatial components (cells and channel) and the applied algorithms in the catchment with AnnAGNPS model. c) Descriptive flow chart of the ephemeral module of AnnAGNPS.

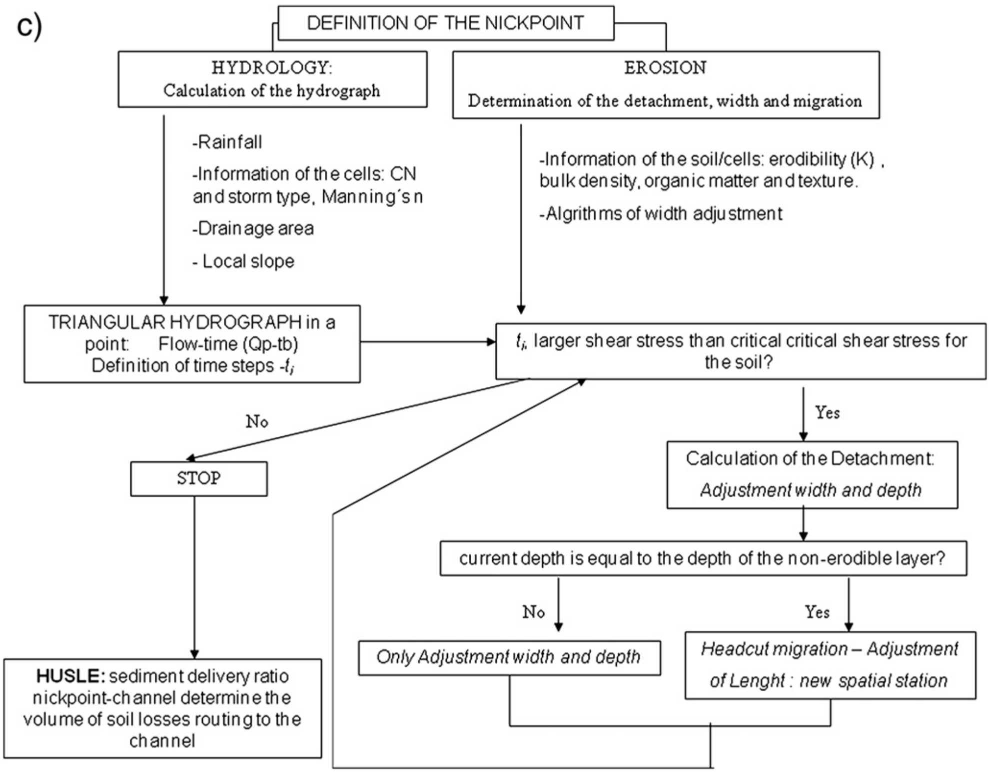

Fig. 3 (*continued*).

ephemeral gully width adjustment and headcut migration (Fig. 3c). Once the incision reaches a non-erodible soil layer, e.g. plow pan or rock bed, a headcut migrates upslope at a rate dependent on flow conditions, field management operations and soil material properties. The lengthwise growth of the ephemeral gully involves a spatially variable flow discharge along the gully due to the variation in contributing area and travel time. Time and space variations are included through the timesteps which divide the triangular hydrograph (TR-55, SCS — Soil Conservation Service, 1986) and the relationships between gully length, drainage area and flow (Eqs. (1)–(3)).

$$A_j = 1 - \left[\frac{L_j}{L_{\max}}\right]^{5/3} \tag{1}$$

$$L_{\max} = 80.3 \cdot {A_d}^{0.6} \tag{2}$$

$$Q_{ij} = Q_{ni} A_j = w_{ij} d_{ij} v_{ij}. \tag{3}$$

where:A_j is the drainage area contributing to discharge at the gully head (ha); L_j is the length corresponding to the upstream location of the migrating gully (m); L_{max} is the maximum ephemeral gully length (m) for a given drainage area A_d (ha) (Leopold et al., 1964); Q_{ij} is the flow discharge at the gully head ($m^3 {*} s^{-1}$); Q_{ni} is the flow discharge at the gully nickpoint ($m^3 {*} s^{-1}$); w_{ij} is the flow width (m); d_{ij} is the mean flow depth (m); and v_{ij} is the mean flow velocity ($m {*} s^{-1}$).

The detachment capacity D_c ($g {*} m^{-2} {*} s^{-1}$) is determined according to Eq. (4) and it is used to calculate the depth of erosion during each timestep DE (m, Eq. (5)).

$$D_{Cij} = k_d \left(\tau_{ij} - \tau_c\right) \tag{4}$$

$$DE_{ij} = t_i \frac{DC_{ij}}{BD} \tag{5}$$

where: k_d is the soil 's erodibility coefficient ($g {*} N^{-1} {*} s^{-1}$) = $29.1 \cdot 10^{-6}.\, e^{-0.224\tau c}$; t_i is the duration of each timestep (s); and BD is the bulk density ($g {*} m^{-3}$).

The algorithms used to calculate the rate of headcut migration are based on physical approximations based on laws of governing mass, momentum, and energy transfer, as developed by Alonso et al. (2002). They are employed during each timestep to determinate the rate of headcut migration (M_{ij}, Eqs. (6)–(7), $m {*} s^{-1}$), and thus a length to which the ephemeral gully has grown (L_j, m). Flow depth (d_{ij}, m) and channel width (w_{ij}, m) are utilized to calculate brinkpoint hydraulics upstream of the headcut.

$$M_{ij} = v_{ij} \sqrt{\frac{\mu_{ij} q_{ij}}{S_D - h_{ij}}} \tag{6}$$

$$\mu_{ij} = 0.5.\rho.k_d.\sin^2\left(\frac{\vartheta ij}{2}\right). \tag{7}$$

where: k_d is the migration headcut erodibility coefficient ($g {*} N^{-1} {*} s^{-1}$) = $0.0001.\tau_c^{-0.5}$; ϑ_{ij} is the jet entry angle (radians); v_{ij} is the jet entry velocity ($m {*} s^{-1}$); S_D is the scour depth, which is taken equal to the tillage depth; h_{ij} is the vertical distance from the brink to the pool surface (m); ρ is the mass density of water ($kg {*} m^{-3}$); and q_{ij} is the unit discharge ($m^2 {*} s^{-1}$).

The adjustments in flow discharge over time (the runoff event) and space (the length of the ephemeral gully) are updated with each successive runoff event. The water associated with an event is routed through the entire ephemeral gully. Finally, only a fraction of eroded sediment – depending on the time of concentration for the cell for inter-rill erosion and of the relationships between the drainage areas of the nickpoint-cell outlet for concentrated flow erosion – is sent to the channel (delivery ratio of sediment from cells to channel, Hydro geomorphic Universal Soil Loss Equation; HUSLE). In the channel, the algorithms of sediment transport determine the final sediment charge (whatever on the sediment source) in the catchment outlet.

The AnnAGNPS input preparation is supported by: 1) an Arc View interface (E.S.R.I., 2000) for managing the data layers (digital elevation model, type of soils and managements) to extract the topography factors (*LS*-factor, travel times), the topology (cell and channels, Fig. 3b), soils and land-use (boundaries of the cells); and 2) by the graphical user interface Input Editor (Bingner et al., 2009) conceived for the organization of the files and for importing information/parameters about the crop and management operations from RUSLE (Renard et al., 1997) databases.

2.3. Data collection techniques and sources

Fig. 4 shows the stages of approach followed by model calibration, generation of the management scenarios and its comparison and economic evaluation.

As is observed in Fig. 4, the runoff and sediment load measurements used in this study correspond to two hydrological years, from September 2005 to September 2007. These events were revised and analyzed and are described in detail in Taguas et al. (2010a). Overall, a total number of 34 events was recorded; in six of them, the sediment loads could not be evaluated and seven of them showed very low runoff values on the sediment sampler. In those cases, minimum sediment loads were observed, with very low values of runoff, so the sediment loads were treated as zero.

The parameters used for modeling can be classified into five categories, as is shown in Table 1.

- The meteorological data used for years 2005–2007 were those recorded at the microcatchment. The *R* factor values are calculated internally for each event applying an equation depending on the daily rainfall (P_d, Eq. (8), Bingner et al., 2009)

$$EI_{30} = 17.9.\exp\left(2.119.\log P_d . e^{\frac{0.0086\log 24}{e^{0.4134\log 24}}}\right). \quad (8)$$

The rainfall record available at the catchment started April 10, 2005. This limits the possibility of evaluating scenarios that could be used to capture the wide year to year variability in precipitation in the region to a small number of years. To overcome this limitation, the two agro-meteorological stations closest to the catchment (less than 15 km away) – the IAS-CSIC Santaealla station and the RIA-Junta de Andalucia–Santaella station – were examined. The former provides a data series from February 1999 until September 2009, while the latter runs from October 2000 until September 2009.

A simple correlation analysis was applied to the monthly and the event rainfall data (Fig. 5). Data series of daily rainfall from the RIA-Junta de Andalucia station showed a correlation coefficient observed at the microcatchment with values equal to 0.88 while 0.79 was the correlation coefficient for data from the IAS-CSIC Santaella station with the observed rainfall values. Although the correlation was a little better in the RIA-Junta de Andalucia station, the series length was shorter. So, the ten-year data series from September 1999 to

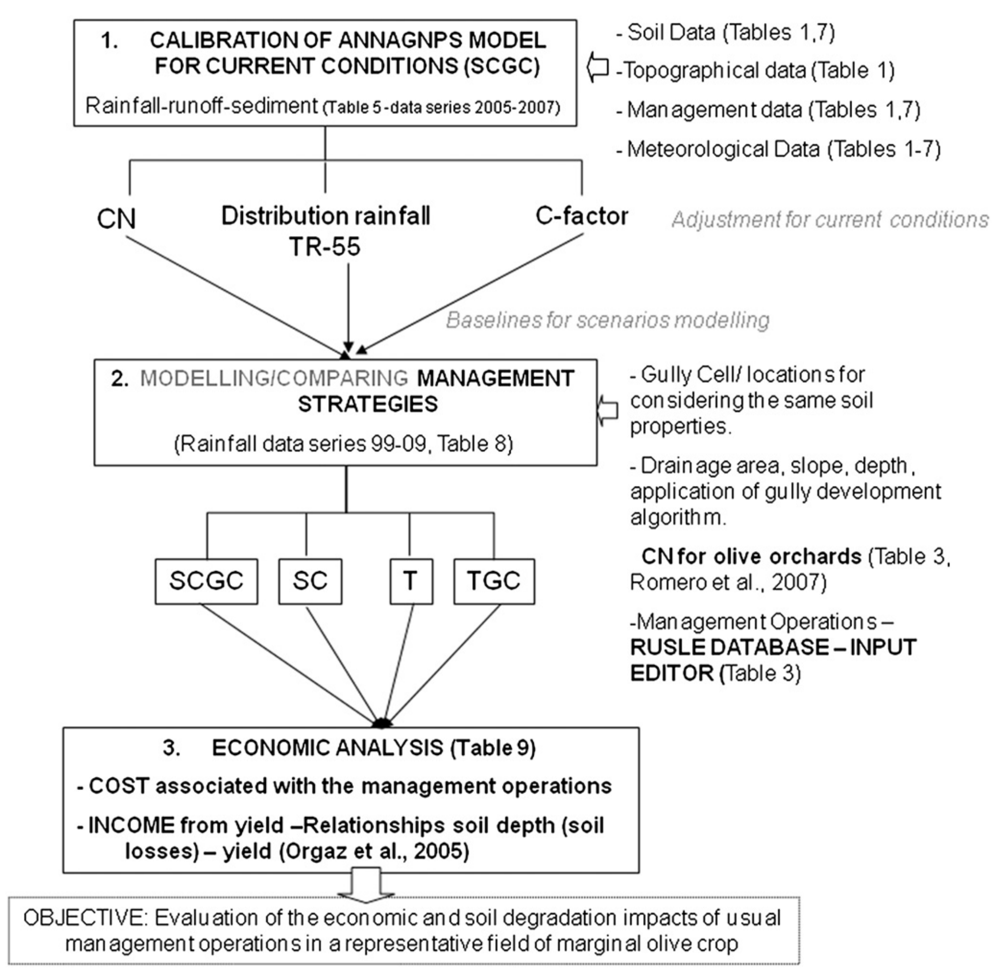

Fig. 4. Description of the approach and stages followed (SC = spontaneous grass cover; T = conventional tillage; SCGC = spontaneous grass cover with ephemeral gully control; TGC = conventional tillage with ephemeral gully control; CN = Curve Number).

Table 1
Input parameters to the model, and references and surveys applied.

Group of parameters	Input variables	Methods
Climate	Daily rainfall	Measurements in the microcatchment.
	Event EI_{30}	Eq. (1) (Bingner et al., 2009).
	Daily maximum and minimum temperatures and wind speed.	Measured in Agrometeorological station of Santaella (CSIC-Cordoba). F.A.O. (1998), using radiation values, latitude, Julian day and daily temperatures.
	Daily % sky covered and dew point temperature.	The distribution that provided the best fit with runoff and peak flow data was chosen.
	Storm type (TR-55)	
Topography	Catchment drainage area, cell area, reach length, mean slope of cells and reaches, LS factors.	Application of TopAGNPS (Garbrecht and Martz, 1999) — Interface Arcview 3.2. (E.S.R.I., 2000), using a DEM (1.5 m × 1.5 m) and field measurements for CSA and MSCL.
Soil data	Depth (horizons)	Field examinations, cleaning of profiles.
(Taguas et al., 2009)	Texture	Traditional method of Robinson pipette (SCS — Soil Conservation Service, 1972)
	Saturated hydraulic conductivity	Philip (1993)
	Bulk density	Mass/volume of clods with wax to measure their submerged weight.
	Field capacity and wilting point	Richard's methodology.
	% organic matter	Methodology of Wakley–Black (Nelson and Sommers, 1982)
	Coarse elements (%)	Observation on aerial photograph and field exams
Management	Crop operations	Annual questionnaires conducted with the farmers.
	C and P RUSLE-factors	Initial values from AnnAGNPS Database (Wischmeier and Smith, 1978) and adjustment according to erosion values. P-factor was equal to 1.
Others	CN	Equation of SCS — Soil Conservation Service (1985) considering values of rainfall–runoff observed.
	Manning's n	TR-55 (SCS — Soil Conservation Service, 1986)

September 2009 collected at the IAS-CSIC Santaella station was chosen to carry out a long term analysis of the management impact. A linear regression between observed-IAS-CSIC data (Eq. (9)) was used to adjust the daily precipitation data at the IAS-CSIC Santaella station in order to correlate the series values better to the observed differences and features in the microcatchment since in this area there is substantial differences of precipitation (Consejería de Medio Ambiente, 2000).

$$P_{obs/sim} = 0.6343 * P_{IAS}\left(R^2 = 0.62; \mathrm{n} = 874\right). \tag{9}$$

Where: $P_{obs/sim}$ is the observed daily rainfall in the catchment; and P_{IAS} is the observed daily rainfall at the IAS-CSIC Santaella station. The variance explained or determination coefficient of the regression is 0.62 ($R^2 = 0.62$). In addition, the daily values of the maximum and minimum temperatures (°C), wind speed ($m{*}s^{-1}$), solar radiation and relative moisture (%) obtained from IAS-CSIC for the 10-year period were used in the simulations.

- The topographic characteristics, such as the drainage area, cell area, length of channels, LS factor, etc., have been extracted using the TOPAGNPS sub-routine (Fig. 4a; Garbrecht and Martz, 1999) integrated in Arc View 3.2. (E.S.R.I., 2000) from a Digital Elevation Model of 1.5 m × 1.5 m × 0.001 m, with a root mean square error of elevation of 0.20 m derived from a photogrammetric flight in December 2004.

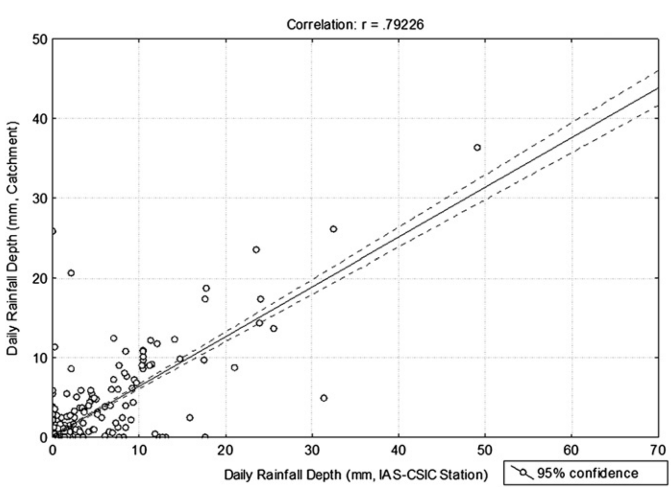

Fig. 5. Correlation among the values of daily rainfall depth in IAS-CSIC Santaella station and the values observed in the study catchment.

The "critical source area" ($CSA = 1$ ha) and the "minimum source channel length" ($MSCL = 150$ m) were estimated in the field, which was the best way to describe the initiation of concentrated flow in order to indentify the cells and streams through the TOPAGNPS subroutine. *CSA* and *MSCL* represent, respectively, the necessary drainage area and the hillslope length for the permanent stream formation under the considered biogeophysical conditions (Table 1).

- The soil properties, including saturated hydraulic conductivity, bulk density, height of the horizons, texture, organic matter, field capacity and wilting point are essential for measuring the soil moisture balance and determining the K factor (erodibility). Therefore, 15 to 30 samples were collected (the number varied, depending on the soil property) and surveys were conducted for the characterization of each cell in the early summer of 2005 (more details in Taguas et al., 2010a).
- The field management operations, timing and details, were obtained from questionnaires conducted with the farmer. From this description the C factors were calculated using the values included in the AnnAGNPS RUSLE sub-module for each management.
- The development of spontaneous grass cover at the end of the winter season and its control in spring was taken into account for the calibration of the C factor through the adjustment of the subfactor "root mass". The initial parameters and sub-factors were taken from the AnnAGNPS database (Oplist.dat). Curve Number (*CN*) values were calibrated from rainfall–runoff measured in the microcatchments (Tables 1), while Manning's n – necessary for the calculation of travel times by determining the concentration time and thus, the peak flow in the outlet – was taken from the TR-55 documentation (SCS — Soil Conservation Service, 1986).

2.4. Calibration of the AnnAGNPS model in the study catchment

2.4.1. Calibration procedure

The calibration was carried out in a logical order according to the input dependencies on each other's runoff, peak flow and sediment yield. The approach described by Yuan et al. (2001) and Licciardello et al. (2007) among others, was followed. Most authors of previous works (Aguilar and Polo, 2005; Yuan et al., 2001) with the AnnAGNPS model, judged that *CN* and *C* were the most sensitive factors for the calibration process. In this study, the *CN*s were determined from the SCS relationships observed in rainfall–runoff according to the moisture level. Since there was not enough information about the *C* factor for olive orchards, the *C*-RUSLE parameters (residue weight ratio, surface/subsurface decomposition residue, moisture depletion, harvest *C-N*, etc.) were selected according to the reference values of rangeland and weeds provided in the RUSLE Cropdata database (which were imported to the module Input Editor). “Root mass” initially derived from the category “weeds” was the adjusting factor modified for simulating the growth of the spontaneous grass cover from February until April. In addition, peak flow depends on the *CN* and the type of rainfall distribution characteristics of different areas in the USA. Therefore, a distribution of 24 h rainfall (SCS — Soil Conservation Service, 1986) was chosen that was more suitable to the data acquired in the microcatchment. Once the topographical features, soil data, operation and management data and the climate file were included, the calibration stages were: 1) adjustment by trial and error, the bi-monthly *CN*s for all the events measured for the corresponding period until the simulation results of the events occurred were reasonably close to the observed values of runoff (Yoo et al., 1993); 2) selection of the storm type that provided the best fit with the all observed peak flows of the data series; and 3) adjustment of the “root mass” sub-factor of *C* to reproduce the erosion values for the events associated to the fortnight following the management patterns. When rainfall did not occur for a month, the values were not altered as in the summer months. In addition, the soil moisture content is the main state variable determining the value of the Curve Number, and therefore, the runoff, peak flow and sediment discharge (Fig. 3a). Although the model allows us to initialize the soil moisture content at the beginning of the period through the weighting of the climatological data included in the input, the calibration for the period September 2005–August 2007 was made without an initialization period, although climatological data input from the period 1st January 2005 onwards (from 2005 from the Santaella-CSIC station) was used. The model's performance was evaluated for quantitative and qualitative approaches where data-display graphics of the observed-modeled values were checked following the fit-sequence runoff, peak flow, and sediment load. The combination of both criteria was considered to determine the *CN–rainfall distribution–C* factor parameterization that provided the best adjustment. The accuracy of the model predictions at the event scale and at the monthly scale (accumulated) was evaluated by comparing predicted with measured values of runoff, peak flow and sediment load based on the model efficiency (*E*) developed by Nash and Sutcliffe (1970). A simple correlation analysis was made between the measured and predicted data, *r*. Finally, the residuals were evaluated by the root mean squared error (*RMSE*), which has the advantage of being in the same units as the observed system output.

2.5. Parameterization of the AnnAGNPS model for the simulation of scenarios

As previously indicated, AnnAGNPS was calibrated for the current soil management used by the farmer adjusting the most suitable Curve Numbers and *C*-factor in the catchment (and selecting the storm type which determine the peak flow; TR-55, SCS — Soil Conservation Service, 1986) to the observed values of rainfall, runoff and sediment record. Afterwards, this parameterization allowed to establish the baseline to simulate three alternative strategies currently used by farmers in the region as options for soil conservation, in order to explore the potential of these alternatives within the context of increased environmental requirements for olive cultivation. The use of grass cover of 1 m (at least) is obligatory in orchards where the mean slope of the field is over 10% in order to receive the subsidies of the Common Agricultural Policy (MMA — Ministerio de Medio Ambiente, 2009), while gully control practices are the result of the farmer's concerns for gully soil losses and the possible impact on crop production. In contrast, tillage remains common in many olive orchards in Andalusia, where it is still being used in an area that is estimated to range from 0.8 Mha (according to our own estimations) to 1 Mha (CAP — Consejería de Agricultura y Pesca, 2002). The farmers repair the ephemeral gullies when they till in readiness for the autumn or/and spring seasons. For all these reasons, the soil management systems studied were spontaneous grass cover and ephemeral gully control (the current management was SCGC), spontaneous grass cover without ephemeral gully control (SC), tillage with ephemeral gully control (TGC) and tillage without ephemeral gully control.

2.5.1. Spontaneous grass cover and ephemeral gully control (SCGC)

The first scenario corresponds to the current situation where the farmer allows the spontaneous grass cover to grow in the lanes (around every tree, herbicide is applied) until mid April, and controls the ephemeral gully development through the use of limestone rocks collected in nearby fields. Table 2 shows the source of the data used for calibration. The sub-factors of *C*-RUSLE factor were calculated according to the reference values of rangeland and weeds provided in the RUSLE Cropdata database (residue weight ratio, surface/subsurface decomposition residue, moisture depletion, harvest *C-N*, etc.), which can be imported to the AnnAGNPS model. “Root mass” was the only parameter modified for simulating the growth of spontaneous grass cover during the year in order to fit the model. In this scenario the lack of ephemeral gully development was simulated through the deactivation of the module for this simulation in AnnAGNPS.

2.5.2. Spontaneous grass cover without ephemeral gully control (SC)

To evaluate the impact of the lack of specific control of ephemeral gullies in the convergence areas of the landscape, this scenario was based on the activation and calibration of the AnnAGNPS module, including the development of ephemeral gullies. Therefore, the parameters considered under the present conditions (SCGC) were maintained and the gully features in the nickpoints were identified (Table 3). The ephemeral gullies were identified by using aerial orthophotography (with a pixel size equal to 5×5 cm) taken in December 2004 and also in the field (Fig. 2a–b). Only the gullies whose widths were greater than 30 cm were identified. During this scenario, which reflects the soil management in the experimental area prior to the monitoring of the basin, the ephemeral gullies were covered as a result of soil operations usually performed in early autumn. They were modeled in AGNPS implementing harvesting operations on November 1st, which included ephemeral gully filling and reshaping. After that date AGNPS allows the re-initiation of the ephemeral gully development. The values of elevation (*Z*), drainage area (*A*) and local slope (*S*) in the nickpoints (Table 3) were evaluated using the slope and flow accumulation maps from Digital Elevation Model of $1.5\ m * 1.5\ m * 0.001\ m$, derived from a photogrammetric flight in December 2004 with Arc View 3.2. (Hydro tools; E.S.R.I., 2000). The erosion depth was related to the first horizon depth, since we could observe that in some gullies only the first horizon and the parental material constituted the soil profile. Finally, the available empirical relationships to width calculations in the AnnAGNPS model (Nachtergaele et al., 2002; Gully-located hydraulic geometry equations; non-submerging tailwater and Woodward, 1999) equilibrium gully width equations (in Bingner et al., 2009) were tested to select those parameters that came closest to real width measurements.

2.5.3. Conventional tillage and ephemeral gully control (TGC)

This scenario reflects the situation when farmers do not use cover crops but carry out erosion control techniques in the area of flow convergence to prevent the development of ephemeral gullies. The calibration, to incorporate the change in soil management on runoff and erosion, was made through the modification of *CN*, *K* (organic matter, bulk density) and *C* factors. No cover was considered and the parameters of residue cover/weight remaining, initial and final roughness and operation tillage depth were imported from the RUSLE Operations database in order to simulate the impact of driving the tractor over the residual cover, while a minimum value of root mass taken from the available literature (Connor and Fereres, 2005) was used. The *CN*-values have been interpolated from the reference values for different managements calculated by Romero et al. (2007) from the adjustment of the data series in olive orchard plots in Andalusia. The relationships corresponding to the “Well-

Table 2
Summary of the main parameters used for the scenario simulation.

Management/used parameters	Spontaneous grass cover and ephemeral gully control (SCGC)	Spontaneous grass cover without ephemeral gully control (SC)	Conventional tillage and ephemeral gully control (TGC)	Conventional tillage without ephemeral gully control (T)
Hydrological parameters	Calibrated CN Manning's n for sheet flow and concentrated flow, values TR-55 (SCS – Soil Conservation Service, 1986)	Calibrated CN Manning's n for sheet flow and concentrated flow, values TR-55 (SCS – Soil Conservation Service, 1986)	CN-relationships between the management practices "Well-established cover crop strip 1 m wide" and "Fresh tilled plow pan" (Romero et al., 2007) Manning's n for sheet flow and concentrated flow, values TR-55 (SCS – Soil Conservation Service, 1986)	CN-relationships between the management practices "Well-established cover crop strip 1 m wide" and "Fresh tilled plow pan" (Romero et al., 2007) Manning's n for sheet flow and concentrated flow, values TR-55 (SCS- Soil Conservation Service, 1986)
Soil and management parameters	Calibrated C factor Measured Ksat Measured BD Measured OM RR (6 mm, Zobeck and Onstad, 1987)	Calibrated C factor Measured Ksat Measured BD Measured OM RR (6 mm, Zobeck and Onstad, 1987) Measured gully features (A_n, S, tillage depth, Table 4)	Calibrated C factor modified by cover values = 0, root mass = 0 and RR Ksat relationships between the managements "No till" and "Fresh-tilled" (Romero et al., 2007) BD-relative reduction between the management practices "cover crop" and "conventional tillage" (Gómez et al., 2009) OM-relative reduction between the management practices "cover crop" and "conventional tillage" (Gómez et al., 2009) RR-freshly tilled 26 mm/RR surface sealing 10 mm (Zobeck and Onstad, 1987)	Calibrated C factor modified by cover values = 0, root mass = 0 and RR Ksat relationships between the managements "No till" and "Fresh-tilled" (Romero et al., 2007) BD-relative reduction between the management practices "cover crop" and "conventional tillage" (Gómez et al., 2009) OM-relative reduction between the management practices "cover crop" and "conventional tillage" (Gómez et al., 2009) RR-freshly tilled 26 mm/RR surface sealing 10 mm (Zobeck and Ostand, 1987) Measured gully features (A_n, S, tillage depth, Table 4)
Algorithms/processes considered in AnnAGNPS model	Rill–inter-rill erosion	Rill–inter-rill erosion Ephemeral gully development	Rill–inter-rill erosion	Rill–inter-rill erosion Ephemeral gully development

Table 3
Values of elevation (Z), drainage area (A) and slope (S) based on aerial orthophotography and erosion depth evaluated in the field.

Gully ID	Zn (m)	A (ha)	S ($m{*}m^{-1}$)	Erosion depth (m)
A	228.39	1.07	0.13	0.05
B	228.87	1.07	0.13	0.05
C	227.06	1.09	0.12	0.05
D	226.49	1.19	0.08	0.05
E	225.72	1.13	0.12	0.05
F	223.41	0.62	0.12	0.05
G	223.17	1.70	0.12	0.20
H	223.66	3.60	0.16	0.05
J	233.78	0.08	0.16	0.05
K	213.42	0.48	0.12	0.05
L	215.17	0.45	0.40	0.05
M	224.42	0.45	0.20	0.05
N	225.47	0.24	0.22	0.05
O	231.29	0.36	0.12	0.05
P	234.75	0.00	0.14	0.05
Q	225.47	0.36	0.13	0.05
R	214.09	0.38	0.20	0.07
Mean	224.98	0.89	0.16	0.06
Dv	6.14	0.85	0.07	0.04
CV(%)	2.7	95.2	46.0	60.7

established cover crop strip 1 m wide" and "Fresh-tilled plow pan" management practices (Table 2) were used to calculate the conventional tillage Curve Numbers from the calibrated *CN*. As for soil properties in olive orchards under conventional tillage, the higher values of the saturated hydraulic conductivity in the first horizon and the substantial reduction in saturated hydraulic conductivity in later results were calculated through the relationships described by Romero et al. (2007) and Gómez et al. (1999), respectively. The relative reduction of bulk density and the organic matter content in the first results observed by Gómez et al. (2009) between the "cover crop" and "conventional tillage" management practices in olive orchard plots were also considered. Finally, the calibrated *C* factor was modified to model the lack of spontaneous grass cover during the year and the impact of tillage operations. Initially, a random roughness of 26 mm was used for freshly-tilled soil and a value equal to 10 mm for modeling the surface sealing (Zobeck and Onstad, 1987). Each year, two tillage operations occur on February 28th and November 15th, on 70% of the field, with a tillage depth of 20 cm.

2.5.4. Conventional tillage without ephemeral gully control (T)

A scenario was developed where a complete lack of soil conservation measures occurs on the olive farm. This was described using conventional tillage soil management mentioned for (TGC) and no control of ephemeral gully development was used in the validation and calibration simulations for the gully formation module in AnnAGNPS in the second scenario SC. For the rest of the calibrated values for the previous, conventional tillage, scenario T (Table 2) was used.

2.6. Cost analysis derived from the management

To obtain a better understanding of the incentives for farmers to implement soil conservation measures in the region, the economic implications for the different management scenarios (SC, SCGC, T, TGC) were explored using a simple model for cost-benefit analysis. The annual cost associated with the management operations, the transformation of olives into olive oil, and the obtained yield income (from harvesting and subsidies) were calculated for each case (SC, SCGC, T, TGC); then, the methodology proposed by Orgaz et al. (2005) was used to relate soil depth and olive yield and for eventually determining the reduction of benefits derived from soil losses. The farmers' income was calculated through the mean price of olive oil (January 2007–May 2009, Spanish Agriculture Ministery, 2009) and the subsidies received by the farmer (CAP — Consejería de Agricultura y Pesca, 2009). The farmers' costs were calculated from the farm operations recorded at the experimental catchment using the data published by Sánchez (2002) updated to 2009 by the CPI (Consumer Price Index) for the period July 99–July 09 (INE — Instituto Nacional de Estadística, 2009).

Based on this information, a relationship between soil depth and olive yield was explored to evaluate the soil losses economically. First, the methodology proposed by Orgaz et al. (2005) was applied to calculate the monthly values of olive crop evapotranspiration (*OET*) while a simple model of water balance in a soil layer (800 mm), where the runoff is based on the calibrated Curve Numbers, was used. Besides *CN*, the inputs used were the mean monthly values of evapotranspiration, the monthly mean rainfall depth (both provided from the Santaella-CSIC station) and soil properties such as the depth of soil, saturation soil moisture, field capacity and wilting point. As for mean rainfall depth values, the annual distribution of rainfall days for the year 2005–2006 was used since it was the most similar to the mean distribution. The monthly accumulated rainfall depth for this period was corrected in order to keep the mean values calculated for the complete series. Finally, the empirical function *OET*–olive yield proposed by Moriana and Orgaz (2003) allowed us to relate olive yield to soil depth and to quantify the net benefit reduction slope expressed in €$*$ha^{-1}$*$year^{-1}.

3. Results

3.1. Calibration

The comparison of observed-simulated values at the event scale and at the monthly scale is presented in Tables 4 and 5. As is observed in Table 4, observed-simulated runoff events reached $E=0.71$ and $r=0.86$ while their *RMSE* is relatively high (1.45 mm) compared to the numerous small events. At the monthly scale, the statistics were improved ($E=0.87$, $r=0.93$ and $RMSE=1.04$ mm, Table 5), which illustrates the model's capacity for producing statistics over a longer duration than just daily events. In the case of peak flows (Table 4). The 24 h rainfall distribution that showed the best results was type II (TR-55), which is the most common one in the USA and is observed in semi-arid states of the south-west whose climate regime is comparable to the Mediterranean. Finally, the sediment loads also showed a similar trend to the runoff with $E=0.70$ and $r=0.87$ at the event scale and *E* and *r* at the monthly scale equal to 0.79 and 0.93, respectively (Tables 4 and 5). Although for both temporal scales, the values provided by the model fitted the observed data reasonably well, a tendency to overestimate the small events and to underestimate the large ones was observed for runoff, peak flows and sediments.

Table 6 presents calibrated values of the key parameters of the AnnAGNPS model for the four scenarios. Under the current management, the mean monthly value of input *CN* (II condition) is 85 in a range from 80 to 96 (standard deviation = 6.2) while for the conventional tillage, the values were between 78 and 84 with an average equal to 80 (standard deviation = 2.3).

Fig. 6 shows the distribution of the *C* values for each 15-day increase throughout the year. As a result of the spontaneous grass cover growth, the average *C* was 0.18 with a standard deviation of 0.07 and a range between 0.09 and 0.33 (Fig. 6a). As can be seen, the minimum *C*-values are associated with the spontaneous grass cover from January to May while the highest occurred in November coinciding with the harvesting operation. In the case of conventional tillage (Fig. 6b), where the soil is kept bare for the whole year, the variations of *C* are very low (average of 0.415, standard deviation of $2.8*10^{-3}$).

3.2. Long-term analysis of the impact management

Table 7 shows a summary of the yearly results of the simulations for the period 1999–2008 and the four scenarios. The average annual rainfall depth is 309.3 mm with a minimum value of 185.9 mm (year 2004–05) a maximum equal to 360.9 mm (2003–04). Four larger rainfall events, with more than 20 mm a day, occurred for the years 2003–04 and 2007–08, while at least two large events (with daily rainfall greater than 20 mm) occurred for each year. The distribution of days with over 10 mm of rain presented a higher variability, ranging from 4 (2008–2009) to 11 (2000–01) events. The runoff values for the four scenarios, SC, SCGC, T and TGC, are presented in Table 7 and Fig. 7. The model analysis predicted great differences in annual runoff as well as in its distribution during the year. The annual runoff (Table 7) was greater and more frequent for the whole period in the case of SC ($m=31$ mm and 10 runoff days$*$year^{-1}) versus the T values ($m=12.3$ mm and 5 runoff days$*$year^{-1}). If the rainfall–runoff relationships (frequency and quantity) are analyzed, a lesser rainfall threshold than 10 mm can generate runoff under the SC while notably larger values are necessary for T management. For the sediment loads the same occurs as for the runoff (Table 7), since it is required for the transport to the outlet. Table 7 and Fig. 7 show how the lowest soil losses was predicted for the SCGC for all the years, while in the case T, except for the year 2002–03, the sediment loads were the highest. Under SC, the most substantial sediment loads occurred from the events in the autumn season due to the highest values of *CN* and *C* factor in the year (Fig. 8). Under T, rainy spring seasons, with higher *CN* derived from soil moisture conditions and high *C* factor (for all year), produced the maximum soil losses for this period. These results, together with an annual rainfall distribution characterized by maximum events occurring in the

Table 4
Observed and simulated values of runoff (Q), peak flow (Qp) and sediment load (sed. load) at an event scale (R = correlation coefficient; RMSE = root mean square error; E = efficiency coefficient of Nash–Sutcliffe, n = sample size).

Date/event	Obs. Q (mm)	Sim. Q (mm)	Obs. Qp ($l*s^{-1}$)	Sim. Qp ($l*s^{-1}$)	Obs. sed. load (kg)	Sim. sed. load (kg)
10-Oct-05	15.920	9.289	351.30	231.00	5693.6	3067.0
11-Oct-05	0.340	1.469	13.60	30.00	[a]	[a]
12-Oct-05	1.500	3.901	45.20	94.00	[a]	[a]
17-Oct-05	0.000	0.108	0.00	0.00	0.0	0.0
30-Oct-05	0.001	0.842	0.04	13.00	0.7	290.0
14-Nov-05	0.014	0.005	1.41	0.00	0.0	0.0
03-Dic-05	0.180	0.000	16.90	0.00	118.9	0.0
28-Jan-06	0.194	0.237	1.90	0.00	135.6	1380.0
19-Feb-06	0.115	0.000	8.30	0.00	16.5	0.0
26-Feb-06	0.015	0.000	0.20	0.00	3.5	0.0
05-Mar-06	0.193	0.000	1.90	0.00	[a]	[a]
19-Mar-06	0.002	0.000	0.01	0.00	0.3	0.0
20-Mar-06	0.340	0.134	35.00	0.00	[a]	[a]
15-Apr-06	0.062	0.144	0.50	0.00	53.5	203.0
03-May-06	0.010	0.060	0.09	0.00	1.5	0.0
04-May-06	0.007	0.000	0.14	0.00	0.2	0.0
14-Sep-06	0.007	0.000	0.25	0.00	1.3	0.0
19-Oct-06	0.600	4.522	40.60	106.00	990.4	1592.0
21-Oct-06	0.040	0.004	0.10	0.00	0.0	0.0
23-Oct-06	0.237	2.019	23.60	42.00	358.4	592.0
25-Oct-06	0.001	0.000	0.05	0.00	0.0	0.0
03-Nov-06	0.027	0.000	0.20	0.00	25.0	0.0
07-Nov-06	0.007	0.000	0.04	0.00	0.0	0.0
16-Nov-06	0.003	0.000	0.05	0.00	0.0	0.0
02-Dec-06	0.020	0.115	0.15	2.00	[a]	[a]
05-Dec-06	0.004	0.081	0.09	0.20	[a]	[a]
02-Feb-06	0.008	0.000	0.06	0.20	9.1	0.0
08-Feb-06	0.004	0.000	0.04	0.00	5.0	0.0
03-Apr-07	0.010	0.000	0.10	0.00	0.5	0.0
09-Apr-07	0.020	0.323	0.30	1.00	3.3	576.0
19-Apr-07	1.030	0.083	86.80	0.00	206.8	0.0
02-May-07	0.750	0.835	12.20	2.00	[a]	[a]
04-May-07	0.010	0.000	1.00	0.00	0.0	0.0
22-May-07	0.040	0.000	0.20	0.00	68.5	0.0
Mean	0.639	0.711	18.892	15.335	284.9	285.2
R	0.86		0.88		0.87	
RMSE	1.450		30.26		588.8	
E	0.71		0.75		0.70	
n	34		34		27	

[a] No sample was collected.

Table 5
Observed and simulated values of runoff (Q) and sediment load (sed. load) on a monthly scale (R = correlation coefficient; RMSE = root mean square error; E = efficiency coefficient of Nash–Sutcliffe, n = sample size; * = incomplete monthly data).

Month	Obs. acc. Q (mm)	Sim. acc. Q (mm)	Obs. acc. sed. load (t)	Sim. acc. sed. load (t)
Oct-05	17.761	15.609	5.6943	3.3570
Nov-05	0.014	0.005	*	*
Dec-05	0.180	0.000	*	*
Jan-06	0.194	0.237	0.0222	0.2262
Feb-06	0.115	0.000	0.0200	0.0000
Mar-06	0.535	0.134	0.0005	0.0000
Apr-06	0.062	0.144	0.0001	0.0000
May-06	0.017	0.060	0.0017	0.0000
Sep-06	0.007	0.000	0.0002	0.0000
Oct-06	0.878	6.541	1.3488	2.1840
Nov-06	0.037	0.000	0.0002	0.0000
Dec-06	0.024	0.115	*	*
Feb-07	0.016	0.081	0.0141	0.0000
Apr-07	1.060	0.406	0.2106	0.5760
May-07	0.800	0.835	*	*
Mean	1.447	1.611	0.6648	0.5767
R	0.93		0.93	
RMSE	1.048		70.77	
E	0.87		0.79	
n	15		12	

autumn and spring seasons, explain why the erosion values were equivalent under both management scenarios for 2002–03.

As far as the ephemeral gully contribution is concerned, the contribution to the erosion derived from ephemeral gullies (Table 7) showed substantial differences depending on the management. The mean sediment loads for the study period have been 2 t∗ha^{-1}∗year^{-1} for SCGC, 3.5 t∗ha^{-1}∗year^{-1} for SC, 3.3 t∗ha^{-1}∗year^{-1} for TGC, and 4 t∗ha^{-1}∗year^{-1} for T with substantial annual variations between 50% and 80%. Under SC, the gully contribution varied from 28% to 59%, with a mean value of 46% while the T range was from 1% to 38% and a mean value equal to 18%. The impact of storms on *CN* and soil moisture associated with the season and the management operations applied (*C* factor, gully repairs) determine the annual response difference for similar annual rainfall depths as observed in Table 7, hydrological years 2000–01 and 2003–04. In this case, for the hydrological year 2000–01, most of the events occurred in the autumn season (Fig. 8) when runoff as well as sediment loads occur as a result of the higher *CN* and *C* factors, whereas if the events had happened for the spring season (hydrological year 2003–2004), lower *CNs* would have meant lower sediment delivery ratios. The maximum values of the ephemeral gully contribution under both managements have been evaluated for the year 2002–03 with the maximum number of rainfall days of the series. Minimum contribution from ephemeral gullies was simulated for the hydrological years 2001–02 and 2007–08 when rainfall was concentrated in the autumn season and the gullies were repaired.

3.3. Cost analysis under different management scenarios

The income from the harvest calculated at the beginning of the simulated scenarios was 829.61 €∗ha^{-1}∗year^{-1} which includes on-site profits and subsidies as is shown in Table 8. For this, a mean olive yield of 5.5 kg∗tree^{-1}, with a tree density of about 200 tree∗ha^{-1} and a transformation ratio olive–olive oil of 21% were considered. Costs from management operations are shown in Table 8 where the highest value is associated with TGC (769.78 €∗ha^{-1}∗year^{-1}) and the lowest with SC (630.18 €∗ha^{-1}∗year^{-1}).

The average soil losses predicted by the modeling exercise were 0.12 mm for SCGC, 0.22 mm for SC, 0.28 mm for TGC and 0.33 mm for T (Table 9), which produced a net benefit reduction of 0.25, 0.47, 0.60 and 0.71 €∗ha^{-1}∗year^{-1}, respectively, due to the decrease in tree transpiration, Fig. 9. Despite the fact that the SCGC is the most environmentally-friendly management practice and is associated with the lowest reduction in yield (Fig. 9), the SC is more profitable, due to lower annual costs. In both cases (SC and SCGC), low net benefits occurred (199.42 €∗ha^{-1}∗year^{-1} versus 103.39 €∗ha^{-1}∗year^{-1}), which illustrates why this is a marginal olive orchard type. In contrast, the TGC provides the lowest benefits (59.83 €∗ha^{-1}∗year^{-1}) and the T management produces the largest reduction in yield and benefits (Table 9). However, differences in benefits due to yield reduction with different management practices are still relatively small, and are only significant after a long period. For instance, periods of 195 years (SCGC) and 70 years (T) respectively, are required to achieve a reduction in profitability of 50 €∗ha^{-1} with the most and the least erosive soil management techniques. This small reduction in profitability can explain the reluctance of farmers to adopt soil conservation measures even at sediment loads that have an impact on the water quality of receiving streams.

4. Discussion

The implications of continuous simulation, the features of the Mediterranean area, and the considerations of scale mean that a previous evaluation of the model is essential. Although it is convenient to increase the data series, the results of the statistics allow us to justify the use of the model to predict runoff and erosion in the study catchment. In the case of runoff, the performance of the model can be compared with the values determined by other authors such as Parajuli et al. (2009), Licciardello et al. (2007) and Yuan et al. (2001). As for sediments, the model's performance is close to that reported by Licciardello et al. (2007), who calibrated the model in a 130 ha catchment in Italy with a 5 year data series, and Yuan et al. (2001), who evaluated the model's performance in a 7 ha catchment in the Mississippi Delta to identify critical areas where protection measurements should be implemented. It can be seen that the calibration statistics respond to the combination of loads of very different magnitudes, and their results were determined by the adjustment of the maximum values. The annual maximum storms were largely responsible for the annual sediment yield in the study data series. Kliment et al. (2008) also found satisfactory predictions of runoff and sediment transport for events associated with intensive, short-term rainfall of a torrential character. However, there is a tendency to overestimate smaller events and underestimate large storms, as other authors have also demonstrated with the AnnAGNPS model (Licciardello et al., 2007; Taguas et al., 2009) and this is a well-known phenomenon in predictions made with USLE (Risse et al., 1993). Finally, the statistics improve at a monthly scale as a result of the model better reflecting long term trends (Yuan et al., 2001).

The use of the model allows us to optimize and to complete the information supported by the data series. Although the ideal approach in carrying out an analysis of the scenarios should be based on previous calibration/validation procedures, the combination of the experimental data and predictions can constitute a useful tool for decision-making and evaluation of the suitability of land-use or the type of soil management. In this case, potential sources of error are associated with inappropriate choices of *CN*s and *C*-parameters, which are the most sensitive parameters of the model (Aguilar and Polo, 2005; Yuan et al., 2001) and were described for defined conditions of land use and management in the U.S.A.. For instance, Risse et al. (1993) cited that USLE provided suitable adjustments for erosion estimation for medium-textured soils with slopes from 3 to 18% and hillslope lengths under 122 m. On the other hand, Soil Conservation Service curve number methodology (SCS-CN; SCS — Soil Conservation Service, 1985) was designed to predict direct event runoff from event rainfall in un-gauged catchments. New Curve Number values have been determined throughout the years to include situations that were not, or were only partially, considered in its original design e.g. crop land-use with sugarcane and pineapple (Cooley and Lane, 1982), reclaimed mines (Ritter and Gardner, 1991), residue and tillage effects

Table 6
Calibration of numerical values and inputs used in the simulation scenarios with the AnnAGNPS model. (fonts — normal: measured values; bold: calibrated values; italic: values calculated for conventional tillage management, see Tables 1 and 3).

Inputs	Values SC/SCGC management		Values T/TGC management	
Distribution of rainfall	**IIa60**		**IIa60**	
CSA (ha)	1.0		1.0	
MSCL (m)	150		150	
Depth (cm)	100	700	100	700
Texture (sand/silt/clay, %)	72.1/18.7/9.2	60.8/34.3/4.9	*72.1/18.7/9.2*	60.8/34.3/4.9
Cell 21	66.3/21.5/12.2	60.8/34.3/4.9	*66.3/21.5/12.2*	60.8/34.3/4.9
Cell 22	72.0/9.5/18.5	60.8/34.3/4.9	*72.0/9.5/18.5*	60.8/34.3/4.9
Cell 23	4.4	5.1	*7.9*	*2.1*
Saturated hydraulic conductivity (horizon, cm/h)	3.8	16.7	*7.6*	*2.1*
Cell 21	8.3	7.9	*11.0*	*3.0*
Cell 22	1.60	1.60	*1.20*	*1.70*
Cell 23	1.70	1.60	*1.29*	*1.70*
Bulk density (g/cm^3)	1.62	1.59	*1.20*	*1.70*
Cell 21	0.17	0.17	*0.17*	*0.17*
Cell 22	0.06	0.06	*0.06*	*0.06*
Cell 23	1.5	1.7	*1.0*	*0.8*
Field capacity	1.6	1.7	*1.1*	*0.9*
Wilting point	1.8	1.8	*1.2*	*1.0*
% Organic Matter.				
Cell 21				
Cell 22				
Cell 23				
C (Mean Annual)	**0.176**		*0.415*	
RR (mm)	**6**		*10 (sealing soil)/26 (fresh till.)*	
PLU	**0.359**		*0.45*	
Manning's n (sheet flow)	0.15		0.2	
P (Mean Annual)	1		1	
CN-II (JF–MA–MJJAS–O–ND)	**80–90–80–96–91**		*78–82–78–84–82*	
Relationship for ephemeral gully erosion–width adjustments	Hydraulic Geometry — Curve A (Mediterranean Climates a = 0.5889, b = 0.38, Bingner and Theurer, 2002)			

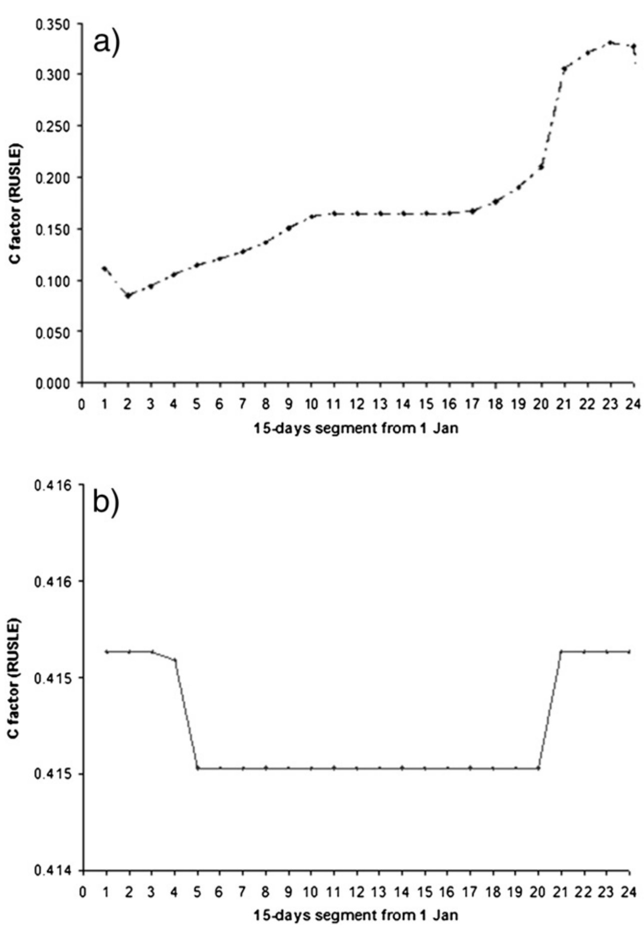

Fig. 6. Annual distribution of *C* RUSLE factor: a) values for SC and SCGC (left); b) annual *C* values for T and TGC (right).

(Littleboy et al., 1996; Rawls et al., 1980), urban areas (Rawls et al., 1981) and olive orchard land-use (Romero et al., 2007). However, the modeling application carried out was based on a review of the erosion studies in olive orchards in Spain, such as Romero et al. (2007) for the selection of CN or Gómez et al. (2003) in the case of the C-RUSLE factor. In addition, the effects of tillage managements (T and TGC) were imported to the Input Editor from the RUSLE database (Renard et al., 1997). Thus, the mean value of *C* factor equal to 0.18 derived from the calibration is comparable to values used by other authors in Mediterranean catchments with olive orchard land use, such as Capolongo et al. (2007) and Märker et al. (2008) with values of 0.11 and 0.30, respectively. In addition, the mean *C* factor for a tilled scenario equal to 0.41 is the same value obtained by Giraldez et al. (1989) for an olive orchard under conventional tillage. Although the uncertainty associated to the impact of *C*-parameterization on gully erosion can be substantial, the weight of *C*-variation in the gully erosion algorithms in AnnAGNPS is low since the main factors controlling the processes depend mainly on the soil physical attributes (Bingner et al., 2009; Fig. 2c). As for the Curve Number, the calibrated values are very close to the reference values in olive orchards for "degraded cover crop with 30% cover" published by Romero et al. (2007) for B and C soil types. It is also significant how the calibrated *CNs* for spontaneous grass cover did not imply less runoff than the values for conventional tillage (Tables 6–7). This has also been observed by other authors such as Romero et al. (2007) with poor or degraded cover or with compacted soils.

On the other hand, the average soil losses simulated for T of $4\ t{*}ha^{-1}{*}year^{-1}$ are practically equal to the measurements of $4.3\ t{*}ha^{-1}{*}year^{-1}$ recorded by Gómez et al. (2008b) in a small 8 ha olive orchard catchment under management with a spontaneous grass cover with tillage operations (at least one per year) where rill and gully erosion were the dominant erosive processes. The average fractions of load related to the development of gullies were equal to 46% and 19% for SC and T may be compared to the values observed in Navarre (Spain) by De Santiesteban et al. (2006) in a small catchment with winter

Table 7
Number of events, annual accumulated values of rainfall depth, runoff and sediment load and contribution from ephemeral gullies for the simulation period (Acc. = accumulated; RD = rainfall depth; SC = spontaneous grass cover; T = conventional tillage; SCGC = spontaneous grass cover with ephemeral gully control; TGC = conventional tillage with ephemeral gully control).

Hydrological year	99–00	00–01	01–02	02–03	03–04	04–05	05–06	06–07	07–08	08–09	**Mean**	**Dv**
Acc. rainfall depth (mm)	316.7	359.3	266.2	339.3	360.9	185.9	324	360.8	344.5	235.6	**309.3**	**60.3**
Number of events RD > 1 mm	43	53	36	58	57	26	50	50	45	37	**46**	**10**
Number of events RD > 10 mm	7	11	7	10	9	6	8	10	8	4	**8**	**2**
Number of events RD > 20 mm	2	3	2	2	4	2	3	2	4	2	**3**	**1**
SC/SCGC-Acc. runoff (mm)	45.0	47.2	28.9	22.1	43.6	4.5	16.2	8.0	54.5	40.2	**31.0**	**17.6**
Events runoff and sed L > 0 (mm, t)—SC and SCGC	10	17	9	13	16	3	10	8	11	6	**10**	**4**
Runoff coefficient (%) SC/SCGC	14.2	13.1	10.9	6.5	12.1	2.4	5.0	2.2	15.8	17.1	**9.9**	**5.5**
T/TGC-Acc. runoff (mm)	13.9	23.1	6.2	5.9	13.0	1.2	2.8	2.2	22.2	12.3	**10.3**	**8.0**
Events runoff and sed L > 0 (mm, t)—T and TGC	4.0	10.0	3.0	6.0	8.0	2.0	3.0	5.0	8.0	5.0	**5.0**	**3.0**
Runoff coefficient (%) T/TGC	4.4	6.4	2.3	1.7	3.6	0.6	0.9	0.6	6.4	5.2	**3.2**	**2.3**
SCGC-Acc. sediment LOAD ($t*ha^{-1}$)	2.2	2.1	2.7	1.1	1.6	0.3	1.1	1.4	5.2	2.1	**2.0**	**1.3**
SC-Acc. sediment load ($t*ha^{-1}$)	3.5	4.3	4.0	2.8	3.4	0.6	2.4	3.1	7.3	3.1	**3.4**	**1.7**
Contribution eph. gullies (%) —SC	37.7	51.8	33.8	59.2	54.9	58.1	53.2	56.2	27.9	31.2	**46.4**	**12.3**
TGC-Acc. sediment load ($t*ha^{-1}$)	3.7	4.0	3.3	1.1	2.9	1.0	2.3	2.9	8.3	4.0	**3.3**	**2.0**
T-Acc. sediment load ($t*ha^{-1}$)	4.3	5.1	3.6	1.7	3.8	1.2	3.0	3.0	9.3	4.6	**4.0**	**2.2**
Contribution eph. gullies (%) —T	13.6	21.5	10.6	37.7	22.5	18.8	24.5	13.7	10.8	13.9	**18.8**	**8.3**

cereals over a period of 6 years, where sediments from ephemeral gullies accounted for 66% of the erosion; 17% was also recorded in another small catchment with vineyards over 2 years. As has been observed, the use of spontaneous grass cover reduces soil losses but the sediment rates from gullies are very substantial under both management practices (SC and T). Therefore, at the study scale, these sediment sources should be well-characterized since the erosion measurements can be seriously miscalculated.

Moreover, the role of rainfall variability is also essential to interpret these results, since much higher soil losses can be produced in a more humid period. In fact, we found in a 61-year (1945–2005) monthly rainfall series analyzed by González-Hidalgo et al.(2011) in Puente Genil, in which, in 68% of the years, rainfall below 500 mm in depth occurred, while in 32% of the years, the annual rainfall depths were under 400 mm.

The translation of the physical data into an economic perspective adds a new dimension to the information available to decision-makers (Smyth and Young, 1998). However, few studies have been carried out to determine the economic implications of erosion (Martinez-Casasnovas et al., 2005), due mainly to the lack of information about the impact of soil conservation measures and to the uncertainty associated with the simulation of scenarios through empirical models such as AnnAGNPS, as well as the use of the relationships proposed by Orgaz et al. (2005) and Moriana and Orgaz (2003). However, this type of work is useful to illustrate the problems farmers and policy-makers face to improve their ideas about soil protection.

In Andalusia, only 33% of the olive orchard area presents smaller olive yield than 1500 $kg*ha^{-1}*year^{-1}$, while 34% are very productive with higher yield than 3000 $kg*ha^{-1}*year^{-1}$ (Parra-López et al., 2005). The main weaknesses that characterize these semi-intensive

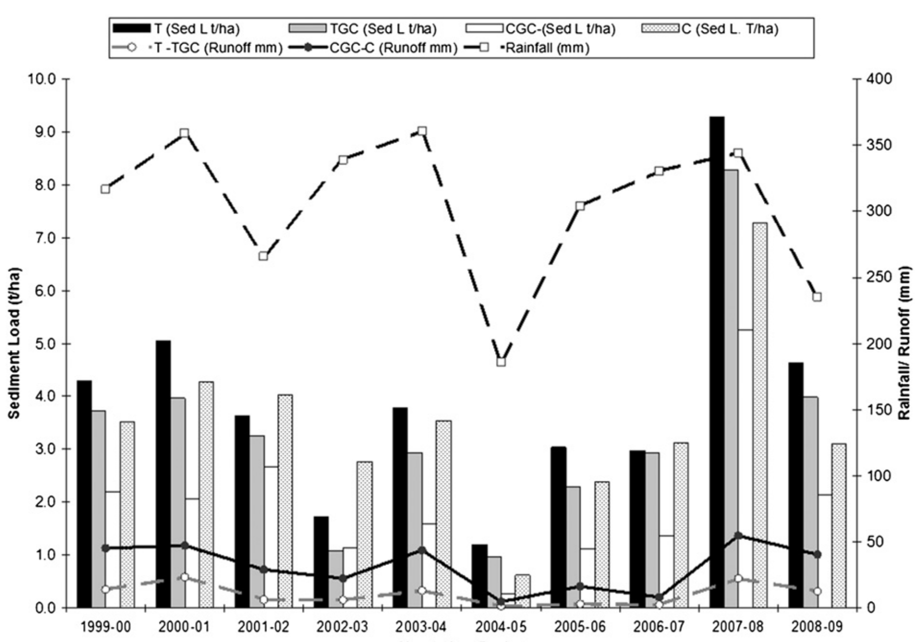

Fig. 7. Comparison of annual values of rainfall depth, runoff and sediment load for the simulation period (SC = spontaneous grass cover; T = conventional tillage; SCGC = spontaneous grass cover with ephemeral gully control; TGC = conventional tillage with ephemeral gully control).

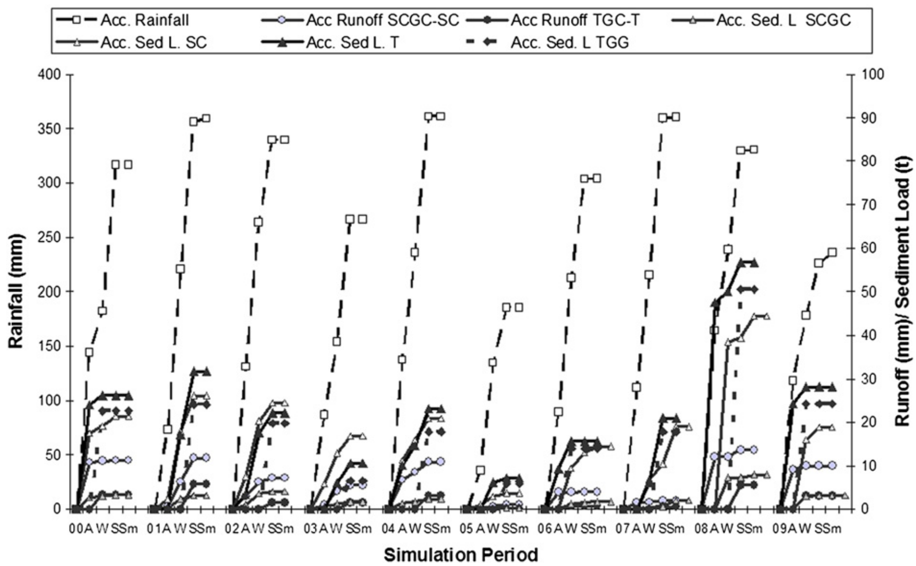

Fig. 8. Seasonal distribution of values of rainfall depth, runoff and sediment load for the simulation period (SC = spontaneous grass cover; T = conventional tillage; SCGC = spontaneous grass cover with ephemeral gully control; TGC = conventional tillage with ephemeral gully control; A = autumn; W = winter; S = spring; Sm = summer).

olive orchards on sloping lands are in ecological sustainability and economic viability (the mean olive yield in the field is equal to 1100 kg∗ha^{-1}∗year^{-1}, Table 9). Ecological sustainability requires better soil water conservation at the farm scale. Economic viability depends on external sources (EU subsidies), productivity and labor costs (Xiloyannis et al., 2008). In our study, the SC/SCGC was the management technique with the lowest rates of soil losses while T/TGC showed the highest soil losses. The profits calculated (between 59.83 and 199.42 €∗ha^{-1}∗year^{-1}) are close to the estimates obtained by Heins (2007) for olive orchards in Southern Spain (between 136 €∗ha^{-1}∗year^{-1} and 281 €∗ha^{-1}∗year^{-1}). This value depends heavily on the topographical slope values, which can lead to a rise in costs due to lower efficiency of the machinery and more working hours. The olive yield improvement associated to the conservation measures is difficult to evaluate on a short term basis. On the other hand, the higher cost associated to SCGC (as compared to SC and T) suggests that, without additional support (such as subsidies for gully control measures) or a stricter linking, and enforcing, of farm subsidies to good agricultural practices such as erosion control, farmers do not have an obvious incentive to use it. Although in some areas in the region, the use of spontaneous grass cover is hampered by the difficulty in obtaining efficient spontaneous grass cover, due to the controls derived from the seasonal rainfall depth, the temperature regime variations and the management operations; in the catchment studied, this approach seems to provide low erosion rates and the best economical return. It seems, therefore that the two most promising approaches to decrease erosion problems in the region are to use these examples as a demonstration for farmers in similar conditions, and to understand why in other conditions shallow till should still be used, despite the higher costs. It is also apparent that further research into economical gully control measures is essential to enhance the adoption of those techniques and reduce the degree of support from agricultural polices

The main inconvenience of the use of spontaneous grass cover is the difficulty in obtaining an efficient spontaneous grass cover due to the controls derived from the seasonal rainfall depth, the temperature regime variations and the management operations applied in previous years such as the herbicide application. In addition, the harvesting operations for the autumn end provoke that the establishment of sown cover for soil protection during the most erosive period was difficult. It is also interesting to analyze why farmers commonly till despite the higher costs — it could be because they associate it with greater infiltration and water storage, and better weed control with tillage. Although our results are based on the impact of the mean soil losses from a 10-year period to illustrate the current situation in the catchment, the impact of extreme storms or large events associated with the Mediterranean regime on the soil losses and on the economic analysis must be considered before judging the results. Further research into economical gully control measures are essential to convince farmers of the need to apply them, especially because 120 years is too long a period to justify their investment in a marginal yield.

5. Conclusions

1. The scenarios simulated to compare the management practices of conventional tillage (T) and spontaneous grass cover (SC), as well as the possible contribution to the erosion from ephemeral gullies (SCGC/TGC) using the AnnAGNPS model suggest that soil losses from ephemeral gullies are a significant source of sediment that should be well characterized so as not to misrepresent soil losses. The lack of information about the improvement on olive yield associated to the conservation measures, the model simplifications and the uncertainty associated with the parameterization chosen and the use of empirical relationships must be taken into account to judge these results and encourage new studies addressing the calibration and validation of erosion models in olive orchards. The rates of sediment loads in the catchment are too low (between 2 and 4 t∗ha^{-1}∗year^{-1}) to provoke short-term intense on-site agronomical and environmental damage. However, the application of gully control measures could mean a large reduction of soil losses for both management practices (46% SC, 19% T).
2. The estimated costs associated with olive yield and soil losses due to losses in transpiration by the tree were 0.25 €∗ha−1∗year^{-1} (SCGC), 0.47 €∗ha−1∗year^{-1} (SC), 0.60 €∗ha−1∗year^{-1} (TGC) and 0.71 €∗ha^{-1}∗year^{-1} (T). These low economic values can explain the lack of damage derived from soil losses in olive orchards perceived by farmers in the study area and similar ones around southern Spain. SC was the most economical alternative while SCGC was the most environmentally-friendly. The study of more economical gully control measurements other than using rock barriers or supporting them, resulting in a cost of about 12% of the annual income, would allow over the long term to equalize the benefits of this expense and provide important information to farmers of their practical application.

Table 8
Summary of annual income received by the farmer and cost analysis derived from the management operations in the study case.

	Olive yield (kg∗ha)–olive oil (21% yield)	Unit price (€∗kg)	Unit value (€∗ha)
Harvest benefits	1100	2.33	538.23
(−) Transformation Costs	1100	0.06	13.54
Subsidies	–	1.32	304.92
Annual income			829.61
Season	Operations SCGC/SC	Components	Unit value (€∗ha)
Autumn	Fertilization NPK 16, manual application.	Fertilizers, 1 farmers	71.70
	Weed control with pre-emergence residual herbicide.	Tractor, 1 farmer, herbicide	40.44
Winter	Soil preparation and olive harvest	Tractor, 8 farmers, rolling	379.99
Spring	Chemical elimination of weeds with herbicide around the trees.	Tractor, farmer, herbicide	40.59
	Tractor driven over the land twice to destroy and limit the vegetation strips.	Tractor, farmer, tires	97.46
Summer	Removal of rocks and their transport to gullies	Tractor, 2 farmers, tools	96.03
Annual costs	SCGC/SC		726.22/630.18
Season	Operations TGC/T	Components	Unit value (€∗ha)
Autumn	Fertilization NPK 16, manual application.	Fertilizers, 1 farmers	71.70
	Weed control with pre-emergence residual herbicide.	Tractor, 1 farmer, herbicide	40.44
	Tillage operations	Tractor, farmer, plow	70.47
Winter	Soil preparation and olive harvest	Tractor, 8 farmers, rolling	379.99
Spring	Post-emergence herbicide	Tractor, 1 farmer, herbicide	40.67
	Tillage operations	Tractor, farmer, plow	70.47
Summer	Removal of rocks and their transport to gullies	Tractor, 2 farmers, tools	96.03
Annual Costs	TGC/T		769.78/673.74

Table 9
Summary of parameters and estimates of the costs derived from soil losses for the different management practices expressed as yield reduction slope, harvest reduction slope and benefit reduction slope (BD I = bulk density in first horizon; SC = spontaneous grass cover; T = conventional tillage; SCGC = spontaneous grass cover with ephemeral gully control; TGC = conventional tillage with ephemeral gully control).

Management practices	SCGC	SC	TGC	T
Sediment load rates (t∗ha∗year)	2.0	3.5	3.3	4.0
BD_I (t/m^3)	1.61	1.61	1.20	1.20
Annual reduction depth (mm)	0.12	0.22	0.28	0.33
Annual yield reduction (kg∗ha∗year)	0.52	0.96	1.23	1.45
Annual harvest reduction (% olive yield)	0.05	0.09	0.11	0.13
Annual reduction benefit (€∗ha∗year)[a]	0.25	0.47	0.60	0.71

[a] Prices obtained (Dec-09) http://www.mapa.es/es/estadistica/pags/PreciosPercibidos/indicadores/indicadores_precios.htm

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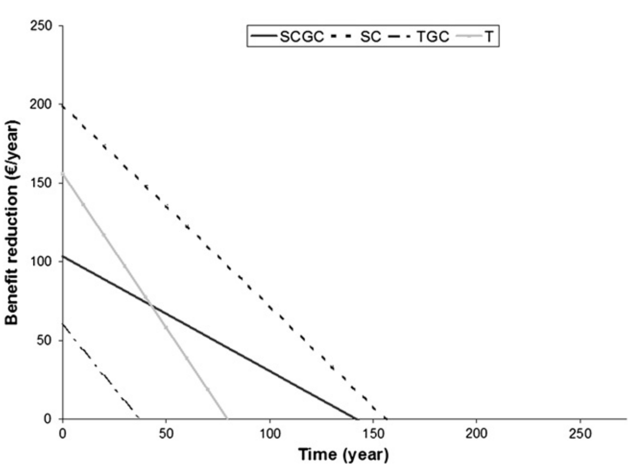

Fig. 9. Reduction of net benefit associated to annual soil losses for the different management practices (SC = spontaneous grass cover; T = conventional tillage; SCGC = spontaneous grass cover with ephemeral gully control; TGC = conventional tillage with ephemeral gully control).

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